Habitability on Kepler Worlds:
Are Moons relevant?
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HABITABILITY ON KEPLER WORLDS: ARE MOONS RELEVANT?

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1. A new approach for the Kepler worlds: an analogy with systems biology

This chapter is based on an extension of previous work and a book review, where additional information has been provided for the interested reader (Chela-Flores, 2011; a; b; 2012a, b). We extend our discussions due to the relevance of the question regarding instrumentation would be suitable for achieving further insights into habitability when we explore satellites from the Solar System, especially our Moon (Smith *et al.,* 2012) and Europa (Gowen *et al.,* 2011), as well as planets and satellites of other solar systems.

We are considering the question of possible relevance of not only the exoplanets that are currently being searched in the over one hundred thousand stars in our galactic neighborhood with the Kepler mission (the "Kepler worlds"), but also their eventually detectable satellites on the bases of the insights we have gathered in our own solar system. Kepler's planets are too faint for a spectroscopic determination of their atmospheric composition. Kepler is designed to merely determine the frequency of Earth-like planets. The next step is finding close-by Earths and analyzing their atmospheres (Kipping, 2012). This significant remark shall be discussed below in Secs. 4 and 6.2.

Astrobiology is a science overlapping the life and physical sciences, but it has surprisingly remained largely disconnected from recent trends in certain branches of both life and physical sciences. We have discussed potential applications to astrobiology of approaches that aim at integration rather than reduction.

Aiming at discovering how systems properties emerge has proved valuable in many fields, including engineering, chemistry and biology. In the case of biology, a good definition of systemics—studying systems from a holstic point of view— considers functional genomics in an attempt to characterize the molecular constituents of life: By discovering how funciton arises in dynamic interactions, this approach to biology addresses the missing links between molecules and physiology (Bruggeman and Westerhoff, 2006).The systems approach should also yield insights in astrobiology, especially concerning the ongoing search for habitability in alternative abodes for life, although at present we have not been able to document sufficiently this approach. However, taking the set of known exo-planets *as a system* is not only feasible, but desirable since new data banks in the case of astrobiology—considering its considerable overlap with the science of biology—are of a geophysical/astronomical kind, rather than the molecular biology data that is used for questions related firstly, to genetics in a systems context and secondly, to biochemistry for solving fundamental problems, such as protein, or proteome folding.

By focusing on how systems properties emerge in astrobiology we raise the question whether habitability can be interpreted as an emergent phenomenon and what role can play exoplanets and exomoons. In the search for potential habitable worlds in our galactic sector with current space missions, extensive data banks of geophysical parameters of exoplanets are rapidly emerging. We suggest that it is timely to consider life in the universe as an emergent phenomenon that can be approached with methods beyond the science of chemical evolution—the backbone of previous research in questions related to the origin of life.

2. An analogy due to the difficulties of habitable zones for allowing evolution of life

New approaches to biology, such as systems biology, still have to make a full impact impact on all branches of biology. This is especially the case for astrobiology, one of the most recent and exciting branches that have a considerable overlap with the life sciences. Research in astrobiology, especially in the origin of life in the universe does not focus on systems as a whole (systems biology); rather it pursues the organic chemical approach of attempting to synthesize DNA, or protein monomers. An approach analogous to systems biology can take advantage of current technological progress to maintain and enlarge the growing fleet of space missions for the exploration of both our solar system and the cosmos at large, and profiting from the broad experience in handling data in both proteomics and genomics.

The related work in complex systems from the point of view of chemistry serves as an additional input to support to the thesis that the systems approach to astrobiology should be explored (Chela-Flores, 2012). The work of P. W. Anderson implies that in chemistry, as well as in biology, the laws that govern its component parts do not regulate exclusively complex systems. In this case, collective behaviour is relevant (Anderson, 1972). This approach has been amply demonstrated subsequently in questions related firstly, to genetics in systems biology (Sauer *et al.,* 2007), secondly, for solving fundamental problems that physicists and computer scientists have faced, such as protein folding (Dobson, 2003, Wolynes *et al.,* 1995), or proteome folding (Hartl *et al.,* 2011; Frydman *et al.,* 2001; Vendrusculo *et al.,* 2011), and thirdly to chemistry in relation to questions closer to aspects of chemical evolution on the early Earth (Szostak, 2009). The well-established areas where systems biology has succeeded are the regulatory networks and mechanisms, amomgst other applications.

The catalogue of known exoplanets is expected to increase rapidly beyond those obtained by astronomical means, such as stellar eclipses, also known as the transit method (Friedlung *et al.,* 2010). Observing a very large number of stars simultaneously where, assuming a random orientation in space, between 0.5% and 10% of the objects will experience an eclipse of a portion of the stellar surface, which will cause a temporary drop in the stellar flux (Mayor *et al.,* 2009). Amongst these new worlds there is a considerable number of possible Earth-sized planets, as well as in super-Earths, which are still likly habitable bodies. In the coming years careful consideration of these putative solar systems will be followed up for definite confirmation.

The data has been retrieved in two stages. Firstly, the French Space Agency (CNES) mission CoRoT (COnvection ROtation and planetary Transits) was launched in 2006 in a Sun-synchronous polar orbit around Earth (Auvergne *et al.*, 2009). The method used is specifically designed to search for transiting super-Earths (1–2 Earth radii) in short-period orbits (<15–20 days, though larger planetary radii are detectable up to periods of 50 days). Secondly, the NASA Kepler mission was launched with a larger telescope. Kepler can remain focused on the same sector in the sky for years and its funding allows it to make observations for a period of 3–4 years having the potential to detect small long-period planets.

The star field that Kepler observes is constrained to the constellations Cygnus and Lyra. The production of data is truly astounding: At the time of writing Kepler had identified 2,326 exoplanet candidates of which 207 are approximately Earth-size (both Earth-like and super-Earths), 1,181 are Neptune-size, 203 are Jupiter-size and the remainder 55 are larger than Jupiter (Borucki *et al.,* 2011b). The earlier Kepler estimate (Borucki *et al.,* 2011a) had identified 5.4% of stars hosting Earth-size candidates, 6.8% hosting super-Earth-size candidates, 19.3% hosting Neptune-size candidates, and 2.55% hosting Jupiter-size, or larger candidates. Multi-planet systems are common: 17% of the host stars have multi-candidate systems, and 33.9% of all the planets are in multiple systems.

3. The Moon and its water content as a mirror of the early Earth

Returning to our solar system the primary scientific importance of the Moon is fundamental, being the closest large body near our habitable planet. On the Moon there is a record that may preserve some signatures of early terrestrial evolution, and of the near-Earth cosmic environment in the first billion years, or so of Solar System history (Chela-Flores, 2011b). This record may not be preserved anywhere else (Crawford, 2004). The manned Moon project was abruptly interrupted only five years after the initiation of the Apollo Missions. However, an enormous boost to astrobiology was given especially due to the lunar samples from six of the Apollo missions during the four-year time interval from1969 till 1972. Altogether the lunar astronauts brought back about 382 kgs of lunar rocks. In addition, three Soviet Luna Missions added a valuable

300 grams from 1970 till 1976. But as we shall see later Antarctica has proved to be a source of meteorites, some of which have a lunar origin. From these sources we have a considerable insight that can be described in terms of a lunar surface that is igneous. In other words, the cooling of lava has formed the rocks. (By contrast, the most prevalent rocks exposed on the Earth's surface due to the presence of water and wind our rocks are “sedimentary”. These include basalts and anorthosites. We know that Moon basalts are in the maria. In the highlands the rocks are mostly anorthosites. Some other rocks in these lunar regions are breccias, namely, fragments produced during collisions in an earlier era and reagglomerated by subsequent impacts. In addition, the Apollo missions returned excellent images, which have been completed with subsequent missions of Solar System exploration.

Although the program of human exploration was cancelled at the beginning of the second decade of the 21st century by the USA, other leading nations have not ruled out the objective of sending astronauts to our satellite in the foreseeable future such as China and India. A principal achievement of the American Apollo Program was being the first “sample-return mission”.

Renewed interest in the Moon included the Japan Space Agency JAXA with the 1990 Hiten spacecraft in orbit around the Moon. The spacecraft released a probe into lunar orbit, but the transmitter failed. In September 2007, Japan launched the SELENE spacecraft, with the objectives of obtaining data of the lunar origin and evolution and to develop the technology for the future lunar exploration.

NASA launched the Clementine mission in 1994, and Lunar Prospector in 1998. ESA launched a small lunar orbital probe called SMART 1 in 2003, in order to take imagery of the lunar surface (X-ray and infrared). SMART 1 entered lunar orbit on November 15, 2004 and continued to make observations until September 3, 2006, when it was decided to crash the spacecraft into the lunar surface to retrieve information on the impact plume. More recently, however, a widespread interest in the exploration of our own natural satellite is increasing. The Lunar Reconnaissance Orbiter (LRO, cf., Vondrak *et al.,* 2010) spacecraft has orbited the Moon on a low 50 km polar mapping mission simultaneously with the Lunar Crater Observation and Sensing Satellite (LCROSS), a robotic spacecraft that succeeded in discovering water in the southern lunar crater Cabeus.

LRO is a precursor to future manned missions to the moon by NASA and other space agencies, for instance, ESA is expected to launch a lander near the Moon’s south pole around 2018. Some new technologies will be tested for future exploration. The difficult terrain of the south-pole region is still attractive due to access to solar power and water ice. The aim of ESA’s proposed precursor mission to visit the Moon’s south polar region is to probe the moonscape’s unknowns and test new technology to prepare for future human landings. To these efforts we should add the Chinese, Indian and Japanese space agencies successes. With these combined global effort in space exploration, especially, Moon exploration, astrobiology is taking some definite steps in answering deep questions about our origins.

4. Habitability on the Kepler worlds and their moons

Satellites of planets and those of exoplanets have been gradually taking the centre stage in habitability. Our satellite was not the exceptional feature of the planets orbiting around our own star, the Sun. It has been suggested that moons in other solar systems—exomoons—are observable (Kipping, 2009a, b). This startling possibility has been realized after the discovery of exoplanets. We must rely on close observation of the motion of potential host planets, because moons themselves are too small to see directly. For example, as the Earth orbits the Sun, it exhibits a slight wobble due to the presence of the Moon. But although we cannot see an exomoon directly, we can still see the effect it has on the host planet. If this planet transits across its star, the planet passes in front of it once every orbital period and a dip in the amount of observed starlight takes place. For every transit, the planet's wobble makes the motion appear slightly differently. These differences would be signatures of a moon due to two changes: firstly, a change in the planet's position, and secondly, a change in planet's velocity (Fossey *et al.,* 2009).

From what we have learnt about the Galilean moons since the appropriately named "Galileo Mission", it is no longer evident that the habitabile zone (HZ), in which planets and their satellites may develop life, need be found in a limited region near the star. In the case of the Solar System, the HZ has been taken to lie outside the orbit of Venus (0.7 AU) and beyond the orbit of Mars (1.5 AU). What we have learnt about Europa, one of the four Galilean moons, suggests that not only can moons in principle be habitable in our own solar system, but suites of extrasolar satellites around exoplanets can in principle also be abodes for life.

We should underline that all that is relevant for life to emerge is the presence of exoplanets, not that an exoplanet be near its companion star. Traditionally the only concept that has led to estimating the boundaries of the HZ has been the reasonable distance of the Earth-like planet from its corresponding star. But the search for life on Europa has exposed the startling possibility that habitability may depend on other factors beyond its appropriate distance from its companion star: for instance, Europa has suggested that even though Jupiter lies outside the HZ 0.7—1.5 AU, we shoud consider whether the satellites may be close enough to a giant planet. For these large bodies may induce ecosystems around hydrothermal-vents that are sources of an adequate inventory of organic elements that may be metabolized by extremophilic-like chemosynthetic microorganisms. Following Kipping and coworkers, we know that a change in a satellite position means that the transit light curve seems to shift about, in what is known as transit time variation, TTV (Sartoretti and Schneider, 1998). The duration of a transit is inversely proportional to the velocity of the planet. So since velocity is changing then transit duration is changing. This manifests itself with the transit duration variation, TDV.

TTV and TDV always exhibit a 90-degree phase shift and this essentially gives astronomers a very unique signature to identify exomoons. If you try to use TTV by itself, you will run into the problem that a plethora of different physical phenomenon can cause TTV, not just moons. By using TTV and TDV together, you can finally say, that signal is definitely a moon. Combining the two approaches just described (TTV or

TDV), allows the calculation of both the mass of the moon and the orbital distance of the moon. Consequently, though Earth-like planets have not yet been detected, and even though giant planets are not evident environments that may support life, the new extrasolar planets are already indicators of possible environments favorable to the origin of life. This conclusion follows from the generality of the arguments of the formation of Jovian planets from their corresponding subnebulae. From the mechanisms for the formation of satellites suggest that in the star cradles in the Orion nebula we should have a similar situation. New instruments will be needed that will improve on the current technology.

The state of the art in detecting the reflex motion began by allowing the detection of star motion due to the presence of a Jupiter-like planet. Indeed, the early examples were all Jupiter-like planets. It is remarkable that the planets themselves that have been detected up to the present are the least likely to be habitable. However, these Jupiter-like planets could have Europa-like satellites—exomoons—possibly candidates for harboring life. This opens the debate as to what are habitable zones, a subject of great interest that we shall not develop in detail here. A habitable zone was understood as one in which the amount of stellar energy reaching a given planet, or satellite, would be conducive to the process of photosynthesis. (Clearly, the amount of greenhouse gases, are relevant too.) Water contributes to the dynamic properties of a terrestrial planet, permitting convection within the planetary crust that might be essential to supporting Earth-like life by creating local chemical disequilibria that provide energy (Schneider *et al.*, 2009). Water absorbs electromagnetic radiation over a broad wavelength range, covering part of the visible and most of the near-IR, and has a very distinctive spectral signature. The search for water at radio wavelengths (1.35 cm) started already 1999 (Cosmovici *et al.*, 2008). Water was also detected in absorption by the Spitzer IR Space Telescope. Abundant water may be likely on some planets since it was detected around the star HD 189733 b (Tinetti *et al.*, 2007; Swain *et al.*, 2008).

5. Data needed for a universe as a complex system with evolutionary convergence

Stars evolve as nuclear reactions convert mass to energy. In fact, stars such as our Sun follow a well-known pathway along a *Hertzprung-Russell* (HR) diagram. They observed many nearby stars and found that in the plot of their luminosity (i.e., the total energy of visual light radiated by the star per second), and surface temperatures, a certain regularity emerges: the stars lie on the same curve in the HR diagram, whose axes are the two parameters considered by the above-mentioned early 20th-century astronomers. Such stars are called *Main Sequence* stars that lie on a diagonal from the upper left of the HR diagram (represented by bright stars) to the lower right (cool stars). We may ask questions that are relevant for our objective of formulating appropriately our concept that the universe may be considered to be complex system: How do stars move on the HR diagram as hydrogen is burnt, and what does it tell us about stellar ages?

Extensive calculations show that main sequence stars are funnelled into the upper right hand of the HR diagram, where we find red giants of radii that may be 10 to 100 times the solar radius. Stellar evolution puts a significant constraint on terrestrial habitability and, in general, on habitability in an exoplanet. For estimating stellar ages, the shapes of the HR diagrams are useful. Stars more massive than about 1.3 solar masses have evolved away from the Main Sequence at a point just above the position occupied by the Sun. The time required for such a star to exhaust the hydrogen in its core is about 5 to 6 Ga, and the cluster to which the Sun belongs must be at least as old. More ancient clusters have been identified. In our galaxy, globular clusters are all very ancient objects, with ages measured in Ga. Exact ages, however, cannot yet be assigned to globular clusters. The details of the evolutionary tracks depend on hydrogen–metal ratios, helium–hydrogen ratios, and the precise theory of stellar evolution. We may expect that the sector of our galaxy that is being probed in the next few years will yield useful data. This forthcoming information can be fed into our model of a universe as a complex system with evolutionary convergence. The data can arise from :

- Kepler astronomical data (KAD). This parameter is related with the age and size of the stellar host of the exoplanets, especially for Earth-like planets in habitable zones that will emerge from Kepler and subsequent missions when such planets are confirmed, following their preliminary identification (Borouki *et al*., 2011a).
- Kepler spectroscopic data (KSD) of anomalous fraction of biogenic atmospheric gases. This parameter is measurable, not only in hot exo-Jupiters that have already been detected by precision infrared spectroscopy with the Hubble Space Telescope, HST, but eventually it is also measurable in super-Earths and Earth-like planets (Tinetti *et al.,* 2007; Swain *et al*., 2008). But eventually we will have some information available on the atmospheres of Earth-like planets in habitable zones. These worlds will begin to emerge from Kepler and in due course from subsequent missions.

These two types of data are intimately related. One aspect of astronomical data concerns the size of the stellar host of exoplanets. This is relevant since stars with mass similar to that of the Sun remain at the red giant stage for a few hundred million years. In the last stages of burning the star pushes off its outer layers forming a large shell of gas much larger than the star itself (a planetary nebula). The star itself collapses under its own gravity, compressing its matter to a degenerate state. The laws of quantum mechanics eventually stabilize the collapse. This is the stage of stellar evolution called a white dwarf. The stellar evolution of stars more massive than the Sun live a shorter life span than stars in the Main Sequence of the HR diagram. Possibly such stars are not old enough to bear an evolutionary line that will produce the gradual atmospheric anomalies that will mean the evolution of life on the exoplanet, or the exosatellite. In the case of the Earth, the theory of stellar evolution tells us that the Sun is a middle-aged star. Even though in the first 4-5 Ga of its existence the Earth has been able to evolve in the Sun's HZ and to preserve a biota, the Kepler astronomical data is relevant for understanding solar evolution. The radius of the Sun is bound to increase, as it moves away from the Main Sequence on the HR diagram, reducing the habitability of the once-habitable planet.

The Sun's expected radial growth will be such that its photosphere will reach the Earth's orbit. This will eventually alter radically habitability on Earth. Likewise in exoplanets, the spectroscopic data will have to be correlated statistically for early-evolved exoplanets with gradual variations of the atmospheric data.

6. Biology other than biochemistry and genetics viewed from a systems approach

ASTROBIOLOGY FROM AN ANALOGY WITH THE SYSTEMS APPROACH

In our theory of life in the universe, we have underlined several stages that are analogous with the standard systems biology, namely:

1. **The theory**: the universe is treated as a complex system with evolutionary convergence, although this is not an intrinsic property of biology, such as hereditability, evolutiionary convergence is rather a consequence of certain genetic and ecological constraints.
2. **The computational modelling**: statistical correlations of astronomical data are needed from Kepler and subsequent missions and spectroscopic data from the Hubble Space Telescope and the next generation of space telescopes.
3. **A testable hypothesis**: the Earth-like exoplanets in habitable zones of Main Sequence stars will yield anomalous fractions of biogenic gases in the spectroscopic analyses of their atmospheres.
4. **Experimental validation**: We need to expand the rapidly growing data banks of exoplanetary searches in the present Kepler and in the future post-Kepler era that will yield sufficient data that is required in our systems astrobiology approach.

In other words, a clear prediction from the present work can be tested in the foreseeable future with feasible instrumentation (to prove, or falsify the theory). We have assumed the universe can be treated as a complex system. Space probes continue to gather large amounts of data concerning measurable parameters from their search for exoplanets. Amongst the forthcoming data there will be the identity of the elements present in the exoplanet atmospheres by spectroscopic means.

To plot at least some point in a figure that shows the correlation between KAD and KSD is a type of quantitative information that would strongly support the idea that the life may originate naturally from the composition of the environment. These correlations will be forthcoming in due course. But at the present time we can begin to illustrate how the data may be handled. As a working hypothesis we have assumed that there will be evolutionary convergence when biology is considered at a cosmic scale. In those planets that are Earth-like and placed within the star's habitable zone the evolution of biota will produce atmospheres that will have an anomalously large fraction of biogenic gases, for example oxygen and methane.

The Kepler Mission data is still gathering in the data banks corresponding to the Earth-like planet candidates that have already been tentatively identified and published (Borucki *et al.*, 2011a). In anticipation to the confirmation of these results we can illustrate the significance of the hypothesis of the universe as a complex phenomenon by referring to an Earth-like planet that we already know with its host star, namely our own planetary system. When more reliable results are obtained in the near future with Kepler and its successors, we will know the anomalous fraction of biogenic gases whenever they are present in the list of Earth-like planets in their own HZ.

In due course we will have a series of graphs one of which is already available and illustrated in Fig. 1. We should take some time to understand what is meant.

6.2 REMARKS ON THE MEANING OF THE HZ OF A G2V STAR

For a sample of planets and satellites in the HZ of a G2V star (cf., the Morgan-Keenan system the stellar spectra), we can return to Fig.1 in which the atmospheres are known. Even though the satellite with atmosphere that is known to us in our solar system (Titan) lies outside the HZ, it could still be a potential habitable body from internal heat sources triggered by its giant planet.

We have inserted an additional exoplanet in the HZ of its own star, whose atmosphere is to be determined in due course. The abbreviations KAD and KSD denote, respectively, the Kepler astronomical data, and the Kepler spectroscopic data. We have suggested plotting the age of the star's confirmed Earth-like planets in its habitable zone (HZ) against the anomalous atmospheric fraction of a biogenic gas (in the present case it is oxygen).

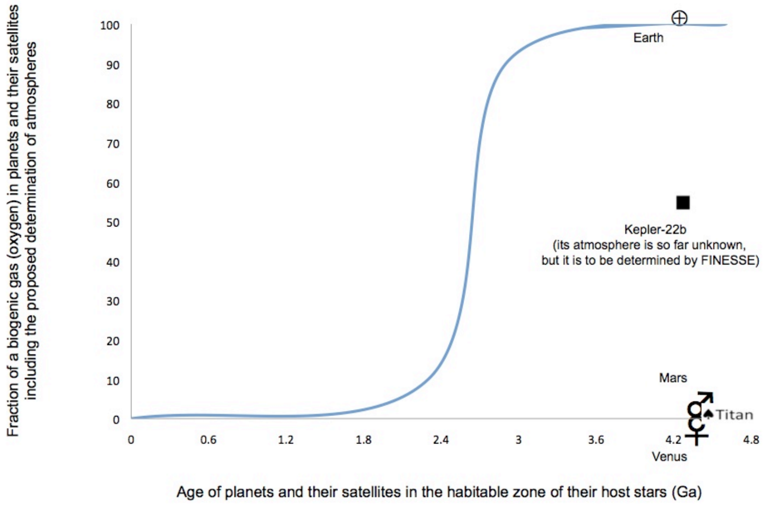

Figure 1. For habitability of planets and satellites: towards an eventual correlation of KAD and KSD.

In the familiar case of the G2V planetary system there are three planets in the star's HZ, but the only appreciable presence of biogenic gas (oxygen) corresponds to the planet at 1 AU from its host star (the Earth). Those at 0.7 AU (Venus) and 1.5 AU

(Mars) have a mainly CO_2 atmosphere (96.5% and 95% respectively, with negligible biogenic gases, hence they were inserted in Figure 1, where we have chosen oxygen as the most relevant biogenic gas in our solar system. To take into account the vital topic of the satellites of the Kepler worlds, we have inserted the one satellite of our solar system that has a considerable atmosphere, but with negligible biogenic gas. The abundant biogenic gas in the planet at 1 AU (Earth) is oxygen. But in other stars the exoplanets in their HZ, such as Kepler-22b (an exoplanet whose age is undetermined, orbiting a G5 dwarf star in the same Class as the Sun, cf., Borucki *et al.*, 2012), could have an anomalous fraction of any of the biogenic gases. Since the time of the origin of the Earth, we have the benefit of knowing even the evolution of the anomalous biogenic gas (oxygen).

For drawing the curve we have assumed that the large increase in oxidation of the atmosphere occurred at 2.45 Ga after the planet's origin (Kump, 2008). By focusing on Sun-like stars of similar age and Class in the Main Sequence of the HR diagram, the data banks will begin to provide evidence for life. For younger stars this illustration (and the corresponding data banks) will not exclude transient episodes of life-bearing exoplanets in their HZ, as may have been the case of Mars at an earlier epoch (Formisano *et al.,* 2004). We have used the standard astronomical symbols for the planets of the Solar System. The black square represents a typical exoplanet in its HZ. We have taken Kepler-22b, whose atmosphere, including any biogenic gas will be determined in due course by NASA's FINESSE.

Later on the anomalous fractions of biogenic gas in other earth-like planet atmospheres (oxygen, methane) will be available for a number of star planetary systems that are within the scope of Kepler, namely, over one hundred thousand stars a sample that we have called KAD. The forthcoming results will contain a subset of Earth-like planets, whose KSD will also be available in the near future with the remarkable present pace of progress in instrumentation. The proportion of anomalous biogenic gas (oxygen) by volume in the atmosphere in the single case of Fig. 1 is some 21 %.

Earlier estimates of biogenic gas in other planets—methane—were attempted with the help of the Hubble Space Telescope for a Jupiter-like planet. For other Earth-like planets, such as the recently confirmed Kepler-22b, the identification of chemical elements in their atmospheres is still a challenge being faced by the Kepler team. But for a Jovian-like planet HD 189733b (Swain *et al.*, 2008) methane was tentatively identified.

Subsequent research, based at the Keck Telescope, has not confirmed this result (Mandell *et al.*, 2011). The confirmation of the preliminary Kepler data of Earth-like planets (KAD) will allow the next step in building of the data banks for the anomalous biogenic gases. In other words, the KSD data could grow into substantial data banks if the present tendency is confirmed (Sec. 2): 5-6% of the preliminary sample of exoplanets are Earth-like. In turn, this implies that some of these will lie in the host star's zone of habitability.

7. Life's fingerprints in the atmospheric gases of the Kepler worlds

Our work is part of a larger body of papers that have discussed biogenic gases as signatures for life. Not only has this topic been advanced in the past, but a new mission is under consideration by NASA (JPL)—FINESSE (Fast INfrared Exoplanet Spectroscopy Survey Explorer)—that would measure the spectra of stars and their planets in two alternative situations that would correspond firstly, to the spectra of both the star and their exoplanets when both are visible, and secondly when the exoplanet is hidden by its star (Swain, 2010). This will allow FINESSE to analyze the planetary atmospheric components (to provide the data that is missing in graphs such as the preliminary one shown in our Fig. 1). Indeed, this JPL proposal would use a space telescope to survey more than 200 planets around other stars. This would be the first mission dedicated to finding out the fraction of biogenic gases in exoplanet atmospheres and how the Solar System fits into the family of planets in the galactic neighbourhood being explored by the Kepler mission.

But returning to recent efforts in the discussion of biogenic indicators of the origin and evolution of life in exoplanets in the context of the present paper, it is worth highlighting:

(i) The development of better models has been suggested for the Earth early atmosphere, including the presence of biosignatures like oxygen (O_2), water (H_2O), ozone (O_3), methane (CH_4), methyl chloride (CH_3Cl) and nitrous oxide (N_2O), in order to be able to select between geophysically produced atmospheres and those that have received an input from biosystems (Kiang, 2008; Darling, 2001).

(ii) In addition to atmospheric biogenic gases such as oxygen, another gas biosignature scientists have already considered is the surface reflectance spectra of vegetation, or the amount of light reflected off plant matter at different wavelengths (Kiang *et al.,* 2007). This work is based on an extension to Earth-like planets in their star's HZ of the events that led to the emergence of oxygenic photosynthesis on Earth (Wolstencroft and Raven, 2002).

We are at an early stage, but in an inexorable route towards the first verification of life elsewhere, microbial or multicellular, either in our own solar system (microbial), as emphasized repeatedly in our earlier research focused on the outer Solar System (Chela-Flores and Kumar, 2008; Chela-Flores, 2010), or (microbial, or multicellular) in other solar systems (Kiang, 2008; Schneider *et al.,* 2009; 2010).

As we have discussed above, the large number of exoplanets being discovered will probably be followed up by a suite of exomoons (cf., Sec. 5). From the hints that have been granted to us by the habitability potential of the Jovian Moon Europa in our planetary neighborhood (Chela-Flores and Kumar, 2008), the range of habitability will be much enhanced.

The implications for the distribution of life can be searched in the potentially habitable planets—Earth-like and placed within the star's habitable zone (HZ). The hypothesis leads to a prediction for a radical change from the atmospheric fractions compared to companion planets (super-Earths and Jovian-like and other planets) in the same stellar planetary systems being explored by the space probes (Kepler and successors, HST and its successors, and by the HARPS Spectrograph).

We are at the very beginning of this search. Earth-like planets in habitable zones of their stars only begin to be known with certainty. At the time of writing Kepler-22b that is 600 light years away and is 2.4 times the Earth's radius, becomes the first in a list of 207 approximately Earth-size planets to have been confirmed, with a subset of 48 actually lying in the HZ of their corresponding stars (Borucki *et al.*, 2011b).

Life in the universe will emerge from statistical analysis of large data banks that are now beginning to accumulate. Our combined assumptions of convergence and the cosmos as a complex system imply that all the Earth-like exoplanets that will be in the HZ of their corresponding star will have an identifiable bioindicator (anomalous production of biogenic gases). The signs of life are predicted to be a biologically produced atmosphere, largely fractionated towards one of the biogenic gases (in the case of the Earth the large fractionation triggered by biosystems is the 21% of oxygen). Such atmospheres would not be the result of natural accretion processes in the processes that give origin to the planets, but instead, the emergence of the biogenic atmospheres would be the result of the innate phenomenon of life that the laws of biochemistry will allow in brief geologic times.

Systems astrobiology is analogous to systems biology, but it has to wait for its full implementation until after we have gathered enough data from the sector of our galaxy that is being probed by the CoROT, Kepler and by subsequent searches. The practical reason why systems biology is a promising frontier for the future of astrobiology is that it is not easy to have access to information on these planets, except through the now incipient data banks of observable geophysical data, such as methane and oxygen atmospheres, as well as information on the presence of liquid water beyond the present data that has already been searched for (Seager and Deming, 2010; Tinetti *et al.,* 2007; Cosmovici *et al.*, 2008).

The search for exoplanets can be viewed as the first step in an eventual discovery of life as a complex cosmic system. Following the lines outlined above, we expect that a rationalization of life will eventually emerge from the data banks of a very large number of stars in our galactic sector. The geophysical data, rather than data banks of biological information, will provide a gradual emergence of the living phenomenon. The geophysical (atmospheric) bioindicators point towards ecosystems that have evolved around stars producing measurable biomarkers in our galactic sector. Subsequently, with better missions and with improved instrumentation, this identification of life as a complex system can be extended from a sector of the galaxy now being probed to other more distant parts of the universe.

To sum up, we have suggested that one evident advantage of viewing the cosmos as a complex system (and life as an emergent phenomenon) is to anticipate, organize and interpret the data that is provided by Kepler, as well as the data that is to come in the post-Kepler/FINESSE era. We have described how the hypothesis of life as a complex system will lead to relevant insights into the whole cosmic system (life and its intimate relation with matter).

8. Retrieving insights into habitability from the lunar surface

Increasing experience that is being provided by the penetrator technology will become gradually a more compelling instrument that will prove its worth as a complement to human exploration of the Moon. The solar wind (SW) is a set of particle expelled from the Sun isotropically at supersonic speeds (several hundred km/s close to the Earth). The SW has irradiated the lunar regolith for over 4 Ga. But more significant still is the fact that an indication of isotopic fractionation of the light biogenic elements on the Moon was already evident from analyses of the lunar samples retrieved by the Apollo and Luna Programme sample-return missions. This geochemical phenomenon is illustrated by the $^{34}S/^{32}S$ rates and the isotopic fractionation in lunar soils is further evidenced in terms of the $^{13}C/^{12}C$ rates. Data from the Apollo 11 lunar bulk fines, breccias and fine-grained basalts excluded biogenic origin, but demonstrated that S and C isotopic fractionation had occurred due to SW impinging on the lunar soils (Kaplan, 1975).

Additional, and significant progress in our knowledge of the Moon and the rest of the Solar System will depend on the adoption of new space technologies. One particularly relevant example is the kinetic micro-penetrator technology. The UK Lunar Penetrator Consortium is preparing to demonstrate the penetrator versatility with the potential identification of biomarkers robotically. Two possibilities are being followed up: an eventual return to the Moon (Smith *et al.*, 2011), as well as the exploration of the Jovian Moon Europa (Gowen *et al.*, 2011). We have argued that support would not only be economically more feasible with penetrators, but that the reward of increasing our data of the lunar regolith and its paleoregolith is full of promising astrobiological returns that are no longer accessible on terrestrial locations.

We have argued that significant relevant data for astrobiology may remain accessible on the Moon soils, due to the total lack of lunar erosion or plate tectonics. Since the predictions that Earth wind (EW) may have implanted relics of the earliest terrestrial atmosphere exclusively on the nearside of the Moon, the case for returning to the farside of our natural satellite with penetrator technology is compelling. In other words, EW is a set of interplanetary particles that impinge on Solar System bodies (including the Moon), whose origin is the Earth, in contrast to SW. The chief motivation for the renewed lunar exploration from what we have discussed above is to ascertain that no traces of EW were ever implanted on the Moon's farside. This task of exploring the lunar surface is feasible by the emplacement of kinetic micro-penetrators bearing a suite of instruments. These would include miniaturized mass spectrometers and miniaturized mass analysers.

These instruments are already available for *in-situ* elemental analysis of a variety of Solar System bodies in the next generation of planetary missions (Rohner et al. 2004; Tulej *et al.,* 2011). The exciting forthcoming new age of space exploration is expected to probe the S patches on Europa's icy surface, in analogy with terrestrial S patches (Chela-Flores 2006, 2010; Gleeson *et al.*, 2010; Gowen *et al.*, 2011). Secondly, as we have argued persistently in the present paper, the next generation of space exploration (Smith *et al.*, 2011) should give a high priority to characterizing the geochemistry of Moon soils, especially the N abundances on the lunar farside, which should have remarkable implications on overlapping areas of the early Earth geophysics and the science of astrobiology.

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